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A L'UNIVERSITE DE PARIS VI

par

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New Technique of Image Multiplexing Using Random Diffuser

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We describe a new technique of image multiplexing which employs a random diffuser. The same diffuser is used to modulate all of the signals to be multiplexed. The signals are recorded on the same frame, making the entire area of the photographic plate available for all of them. The decoding is done by putting a binary filter in the Fourier plane where each signal produces a system of rectilinear fringes. We get the product of the signal function and the diffuser function as the retrieved image. The maximum number of signals that can be stored without cross talk is a function of the number of exposures for each signal and the interexposure displacement of the signal on the photographic plate. This is limited by the dynamic range of the photographic emulsion and the precision of the displacements of the photographic plate.

INDEX HEADINGS: Image formation; Photography.

Several techniques have been suggested for image multiplexing in holography as well as in ordinary photography. The methods of multiplex image storage are based on modulating the signal with spatial carriers.[1] Leith and Upatnieks[2] used different carriers for different spatial signals. Collier and Pennington[3] and Caulfield[4] have recorded different spatial signals on different areas of the hologram, avoiding any overlapping. The theta modulation suggested by Armitage and Lohmann[5] makes use of angular orientation of the grating, defined as the azimuth angle, as a parameter for modulation. A similar method was described by Mueller[6] which uses, unlike the method of Armitage and Lohmann,[5] a single carrier frequency; this requires no interlacing of image elements and the carrier angles are independent of the image irradiances. The high rotational and wavelength sensitivity and, consequently, the possibility of critical alignment of the hologram between the read-out beams, makes the recording medium capable of storing a multiplicity of images, each produced with a differently oriented read-out beam.[7,8] Another technique, which makes use of the entire area of the photographic plate to record the hologram of each of the signals to be multiplexed and which uses a single carrier frequency, has been proposed by Som and Lessard.[9]

The present technique resembles carrier multiplexing but does not employ the conventional carriers, such as the Ronchi grating. A random diffuser is used to modulate the signal, which is recorded twice on the same photographic plate with a small displacement between the exposures. In the retrieval process, the Fourier transform of the signal is modulated by a system of cosine fringes. In this technique, as in Mueller's,[6] several overlapped signals are recorded on a single frame, using the entire area of the photographic plate for each signal. The linear-frequency storage capability of the film plays an important role in the success of this method.

In this paper, we shall describe the use of carrier-frequency photography using a random diffuser to provide a technique for multiplex image storage. Experimental results will be given to support the theoretical arguments, followed by a brief discussion of the quality of the retrieved images. The theoretical limit imposed by the technique on the maximum number of images that can be multiplexed will be considered. The dynamic range of the photographic emulsion imposes a further restriction on the total number of signals. The major drawbacks of the technique and the limitations imposed by the mechanical adjustment will be pointed out.

PRINCIPLE

Two light distributions, identical in all respects but displaced slightly relative to each other, give, in the Fourier plan, a system of Young's fringes.[10] The interfringe spacing and the orientation of the fringes depend, respectively, on the amount and the direction of the lateral displacement of the two light distributions. Let an opaque screen, with a small aperture pierced through it, be placed in the Fourier plane in such a manner that the aperture coincides with one of the fringe maxima. This passes the information carried by the fringe system. If the aperture is displaced so that it coincides with a fringe minimum, no information will be transmitted. When there are two systems of fringes with different spatial frequencies, some of the maxima of one system will coincide with some of the minima of the other. In other words, in the Fourier plane, there will be points that contain information from only one of the systems. If the aperture is centered at such points, information carried by that system will be passed whereas that due to the other will be stopped.

The two identical but laterally displaced light distributions are obtained by recording the given signal twice on a photographic plate and translating it through ξ_0 in its own plane perpendicular to the optical axis of the imaging system. After development, such a photographic plate, when placed in a coherent optical processor, gives rise to a system of linear fringes in the Fourier plane. Two signals that are to be multiplexed can be recorded on a single frame, so that the two dissimilar pairs of light distributions originate from the same plane. The signal is modulated by a diffuser in order to get a well-spread-out field for the system of Young's fringes.

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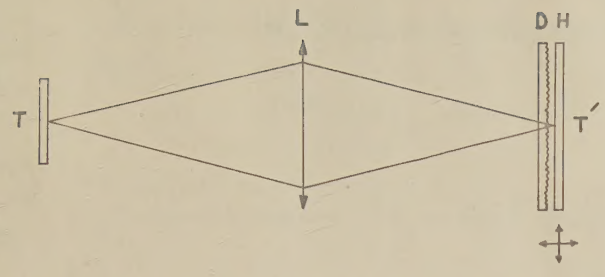

FIG. 1. Optical arrangement for recording multiple images.

This forms the basis of the proposed technique for image multiplexing. Further development to improve the storage capacity of the technique will be discussed in subsequent sections.

THEORY

Two Exposures

Figure 1 shows the recording geometry; T′ is the image of a transparency T formed by lens L on the photographic plate H; D is a diffuser, placed immediately before the photographic plate. The distance between the diffuser and the plate is so small that for all practical purposes the image T′, the diffuser D, and the photographic plate H can be considered to lie in the same plane.

Let $G(\eta,\zeta)$ characterize the irradiance distribution in the image T and let $D(\eta,\zeta)$ be the transmittance of the diffuser. At any arbitrary point on the photographic plate the irradiance received is the product $G(\eta,\zeta)\times D(\eta,\zeta)$. Let the photographic plate be given a translation ζ_0 in its own plane and perpendicular to the optical axis of the imaging system. In this case, the irradiance at the same point will be

$$G(\eta,\ \zeta-\zeta_0)\times D(\eta,\ \zeta-\zeta_0).$$

If the photographic plate is given two successive exposures under the above-mentioned conditions, the total exposure recorded is

$$\mathcal{E}(\eta,\zeta)=[G(\eta,\zeta)\times D(\eta,\zeta)]+[G(\eta,\ \zeta-\zeta_0)\times D(\eta,\ \zeta-\zeta_0)]. \quad (1)$$

The plate, after development under the usual conditions of linearity, is mounted in the optical processor shown in Fig. 2, where it is illuminated by a parallel beam of coherent light. The amplitude transmitted by the plate is

$$t_n=t_0-\beta_0\{[G(\eta,\zeta)\times D(\eta,\zeta)]+[G(\eta,\ \zeta-\zeta_0)\times D(\eta,\ \zeta-\zeta_0)]\}, \quad (2)$$

where t_0 and β_0 are constants. At a point (u,v) in the focal plane F of the lens L′, the amplitude distribution is given by

$$U(u,v)=\mathrm{FT}[t_0]-\beta_0\{\mathrm{FT}[G(\eta,\zeta)\times D(\eta,\zeta)]+\mathrm{FT}[G(\eta,\ \zeta-\zeta_0)\times D(\eta,\ \zeta-\zeta_0)]\}, \quad (3)$$

where FT denotes the Fourier transform. Equation (3) can be simplified as

$$U(u,v)=\mathrm{FT}[t_0]-\beta_0[1+\exp(jkv\zeta_0)]\times\{\mathrm{FT}[G(\eta,\zeta)]\otimes\mathrm{FT}[D(\eta,\zeta)]\}, \quad (4)$$

where $\otimes$ is the symbol for convolution and $k=2\pi/\lambda$. The first term on the right-hand side of Eq. (4) represents the direct image of the source that is located at the focus of the lens L′. This is quite small and occupies a negligible field. In the second term, apart from a constant, the factor $\mathrm{FT}[G(\eta,\zeta)]\otimes\mathrm{FT}[D(\eta,\zeta)]$ is modulated by the factor $[1+\exp(jkv\zeta_0)]$, which corresponds to a system of Young's fringes in the plane F (Fig. 2). These fringes are perpendicular to the direction of translation. In Fig. 3 $\cos^2 kv\zeta_0/2$ is proportional to the irradiance of the fringes, and also to the real part of the amplitude. Now, if ζ_0 is small, the fringes are quite broad; consequently, the adjacent maximum and minimum are well separated. If an opaque screen, with a small aperture pierced through it, is placed in the plane F in such a manner that the aperture falls on one of the maxima, the first term on the right-hand side of Eq. (4) is stopped, whereas the factor $[1+\exp(jkv\zeta_0)]$ becomes constant. Thus, on the other side of the aperture, only $\mathrm{FT}[G(\eta,\zeta)]\otimes\mathrm{FT}[D(\eta,\zeta)]$ multiplied by a constant is transmitted. One more Fourier transformation restores the required distribution $[G(\eta,\zeta)\times D(\eta,\zeta)]$. It is obvious that, instead of an opaque screen with a single aperture, an array of slits can also be used. These slits can be made to coincide with the maxima of the fringe system. A translation through half the period of the array will make the transmittance equal to zero. A convenient expression for the slit system can be obtained by convolution of a rectangular function with a Dirac comb of suitable frequency.

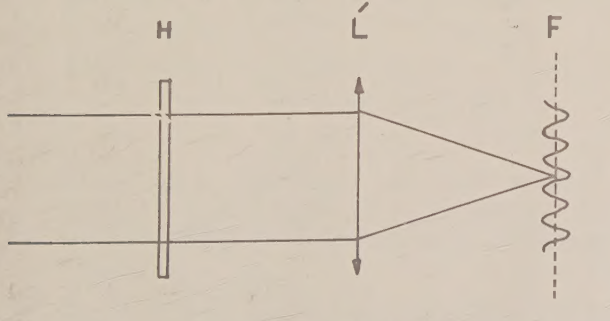

FIG. 2. Optical arrangement for retrieval of multiple images.

Let two signals with irradiance distributions $G_1(\eta,\zeta)$ and $G_2(\eta,\zeta)$, independent of each other, be recorded on the same photographic plate, one after the other. For each signal two exposures are made with translations ζ_1 and ζ_2, respectively, between the exposures. The total exposure recorded is

$$\mathcal{E}'(\eta,\zeta)=[G_1(\eta,\zeta)\times D(\eta,\zeta)]+[G_1(\eta,\ \zeta-\zeta_1)\times D(\eta,\ \zeta-\zeta_1)]+[G_2(\eta,\zeta)\times D(\eta,\zeta)]+[G_2(\eta,\ \zeta-\zeta_2)\times D(\eta,\ \zeta-\zeta_2)]. \quad (5)$$

After development, the amplitude transmittance is

$$t_n' = t_0' - \beta_0'\{[G_1(\eta,\zeta)\times D(\eta,\zeta)] + [G_1(\eta,\zeta-\zeta_1)\times D(\eta,\zeta-\zeta_1)] + [G_2(\eta,\zeta)\times D(\eta,\zeta)] + [G_2(\eta,\zeta-\zeta_2)\times D(\eta,\zeta-\zeta_2)]\}, \quad (6)$$

where t_0' and β_0' are constants.

In the focal plane F, the amplitude distribution is given by

$$U'(u,v) = \mathrm{FT}[t_0'] - \beta_0'[1+\exp(jkv\zeta_1)] \times\{\mathrm{FT}[G_1(\eta,\zeta)]\otimes\mathrm{FT}[D(\eta,\zeta)]\} - \beta_0'[1+\exp(jkv\zeta_2)] \times\{\mathrm{FT}[G_2(\eta,\zeta)]\otimes\mathrm{FT}[D(\eta,\zeta)]\}. \quad (7)$$

Again, the first term represents the image of the source at the focus of the lens. The modulating factors $[1+\exp(jkv\zeta_1)]$ and $[1+\exp(jkv\zeta_2)]$ correspond to two systems of Young's fringes, as shown in Fig. 4. The phase lag between the two systems will depend on ζ_1 and ζ_2. As shown in Fig. 4, some of the maxima of system I can be made to coincide with the minima of system II, so that a system of slits centered at such places would let pass only one distribution, i.e., that corresponding to system I. At the same time, it is not possible to have the maxima of system II coincide with the minima of system I. However, when $\zeta_2 \neq \zeta_1$ (Fig. 4) at minima of system I, there is a finite amount of light flux due to system II. An aperture placed at a place like A (Fig. 4) will let pass only the second distribution. For $\zeta_2 = \zeta_1/2$, the flux at A due to system II is 0.5 I_{max}. This can be increased by assigning a lower value to the ratio ζ_2/ζ_1.

Multiple Exposures

In order to store a large number of images, it is necessary to decrease the width of the bright fringes and at the same time increase the width of dark fringes. This can easily be brought about by generating a system of multiple-beam fringes of the type given by a series of linearly arranged pinholes. The photographic plate can be multiply exposed to a given irradiance distribution, with small equal displacements of the plate between the exposures. The finesse of the fringes so produced depends on the number of exposures. Such a system of fringes has been described by Burch and Tokarski[11] and is identical to those in multiple-beam hologram interferometry.[12] Continuing to use the same notations, we can write the total exposure received by the photographic plate in $(N+1)$ exposures,

$$\mathcal{E}(\eta,\zeta) = [G(\eta,\zeta)\times D(\eta,\zeta)] + [G(\eta,\zeta-\zeta_0)\times D(\eta,\zeta-\zeta_0)] + [G(\eta,\zeta-2\zeta_0)\times D(\eta,\zeta-2\zeta_0)]\cdots + [G(\eta,\zeta-N\zeta_0)\times D(\eta,\zeta-N\zeta_0)].$$

All of the N translations have been assumed to be equal. The plate is developed and is placed in the linear processor of Fig. 2. The amplitude at the focal plane of L′ is given by

$$U(u,v) = \mathrm{FT}[t_0] - \beta_0\{[1+\exp(jkv\zeta_0)+\exp(2jkv\zeta_0)\cdots + \exp(Njkv\zeta_0)]\times\mathrm{FT}[G(\eta,\zeta)]\otimes\mathrm{FT}[D(\eta,\zeta)]\},$$

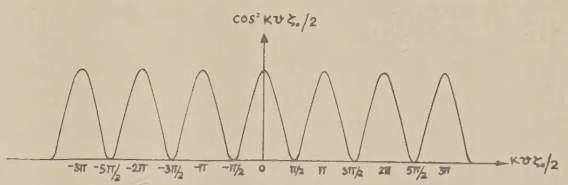

FIG. 3. Fringe system due to a signal recorded twice with a small displacement ζ_0 between the exposures.

which simplifies to

$$U(u,v) = \mathrm{FT}[t_0] - \beta_0\left\{\frac{1-\exp[jkv(N+1)\zeta_0]}{1-\exp(jkv\zeta_0)}\right\} \times\mathrm{FT}[G(\eta,\zeta)]\otimes\mathrm{FT}[D(\eta,\zeta)]. \quad (8)$$

Again, the first term corresponds to the undeviated image of the source. The convolution of the Fourier transforms of G and D is now modulated by a function

$$\frac{1-\exp[jkv(N+1)\zeta_0]}{1-\exp(jkv\zeta_0)},$$

which corresponds to a system of fringes of the type

$$\frac{\sin^2[kv(N+1)\zeta_0/2]}{\sin^2(kv\zeta_0/2)}.$$

Such fringes are obtained from a system of $(N+1)$ equidistant pinholes of equal transmittance. Two main maxima are separated by $(N-1)$ equally spaced secondary maxima, the irradiances of which can be taken, for all practical purposes, to be zero if N is large.

In the presence of two dissimilar signals recorded on the same frame, Eq. (8) will be

$$U'(u,v) = \mathrm{FT}[t_0'] - \beta_0'\left[\left\{\frac{1-\exp[jkv(N_1+1)\zeta_1]}{1-\exp(jkv\zeta_1)}\right\} \times\mathrm{FT}[G_1(\eta,\zeta)]\otimes\mathrm{FT}[D(\eta,\zeta)] + \left\{\frac{1-\exp[jkv(N_2+1)\zeta_2}{1-\exp(jkv\zeta_2)}\right\}\times\mathrm{FT}[G_2(\eta,\zeta)] \otimes\mathrm{FT}[D(\eta,\zeta)]\right]. \quad (9)$$

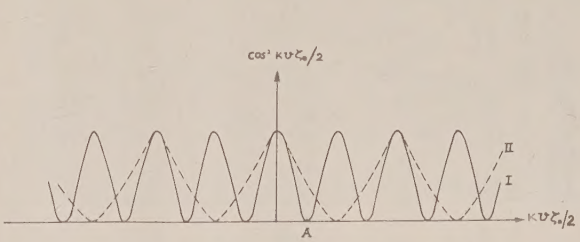

FIG. 4. Fringe system due to two independent signals recorded with displacements ζ_1 and ζ_2 between the exposures of the two signals.

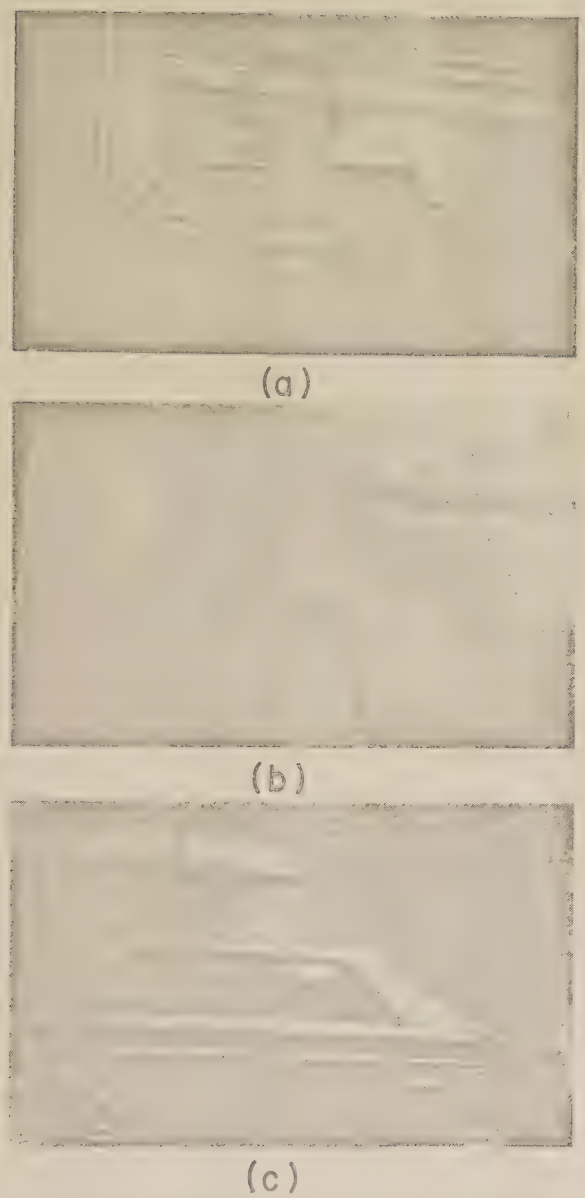

FIG. 5. (a) Two-exposure recording of two images, $\zeta_2:\zeta_1=2:1$; (b) and (c) retrieved images from (a).

N_1, N_2 and ζ_1, ζ_2, are, respectively, the numbers of exposures and the displacements corresponding to the two systems of fringes. Proper selection of ζ_1 and ζ_2 displaces the two systems of fringes relative to each other. The sharpness of the fringes makes possible the accomodation of a large number of images without any cross talk.

EXPERIMENTS

The recording geometry is shown in Fig. 1, where the transparency T is illuminated by a coherent beam of light. Lens L forms its image at T′, where a diffuser D is placed. Immediately behind the diffuser is the photographic plate H, which records the image. The photographic plate is mounted on a kinematic cross slide that is provided with two motions, parallel and perpendicular to the optical axis of the imaging system. The motions are controlled by micrometer screws in order to produce precise movements. The movement along the optical axis, perpendicular to the plane of the plate, is used to adjust the distance between the plate and the diffuser.

In the retrieval system of Fig. 2, a slit is aligned with the fringes in the plane F. It is mounted on a carriage that displaces it in a direction perpendicular to the fringes.

Results have been presented for two types of storage, (a) using the two-exposure technique and (b) using multiple exposures. Figure 5(a) shows the composite two-exposure record of two signals on a single frame. The displacements between the two exposures in the two cases were in the ratio 2:1. Figures 5(b) and 5(c) show the retrieved images from the recording shown in Fig. 5(a). In Fig. 6, the retrievals from another recording are shown; this time each signal was multiply recorded. The improvements brought about as a result of multiple exposures are quite apparent. A three-image recording is shown in Fig. 7(a); its Fourier transform is shown in Fig. 7(b); the three systems of multiple-beam fringes can be easily identified. Some fringes are common to two or more signals. In order to have a minimum number of such overlapped fringes, the chosen values of ζ_0

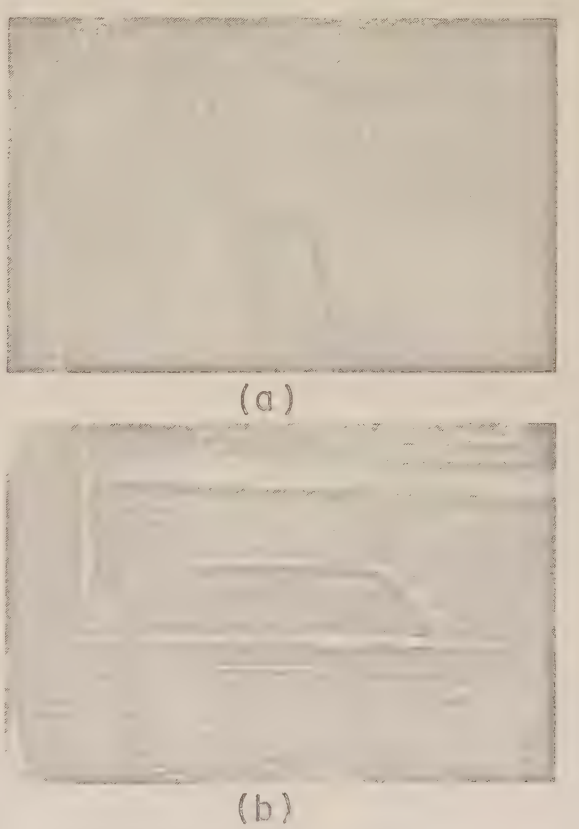

FIG. 6. Retrievals from a multiple-exposure recording of two images.

should not be multiples of one another. The retrieved images from this recording are shown in Figs. 8(a), 8(b), and 8(c).

The granular structure seen in all of the retrieved images is attributed to the fact that the product of the signal and the diffuser functions is reconstructed. Moreover, the presence of the spatial filter modifies the diffuser function. The spurious details shown up are due to diffraction at the various optical surfaces.

DISCUSSION

Channel Capacity

The total number of images that can be retrieved without any cross talk, after having been recorded on a single frame, depends on the finesse of the multiple-beam fringes in the Fourier plane. In this plane, the function

$$\frac{1-\exp[jkv(N+1)\zeta_0]}{1-\exp(jkv\zeta_0)}$$

that modulates the convolution

$$\mathrm{FT}[G(\eta,\xi)]\otimes\mathrm{FT}[D(\eta,\xi)]$$

corresponds to a system of fringes of the type

$$\frac{\sin^2[kv(N+1)\zeta_0/2]}{\sin^2(kv\zeta_0/2)}. \tag{10}$$

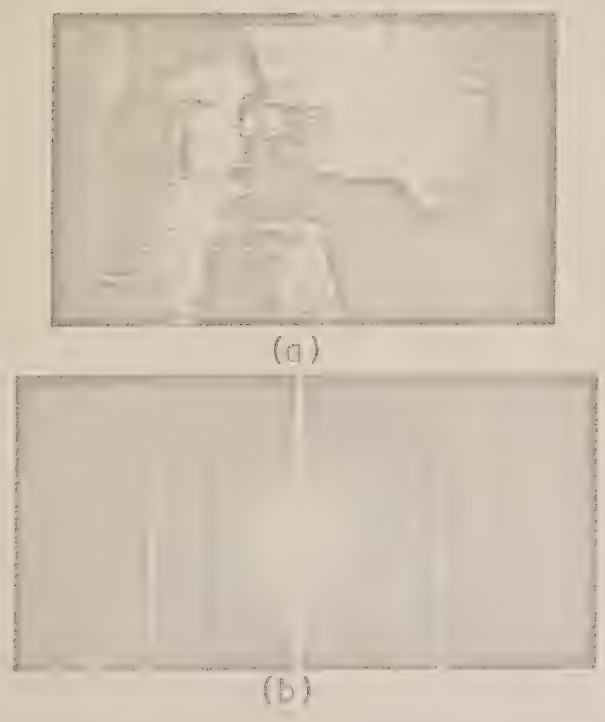

FIG. 7. (a) Multiple-exposure recording of three images. Equal displacements of the signal were made between the exposures: $\zeta_1:\zeta_2:\zeta_3=4:5:6$. (b) Fourier transform of the recording shown in (a).

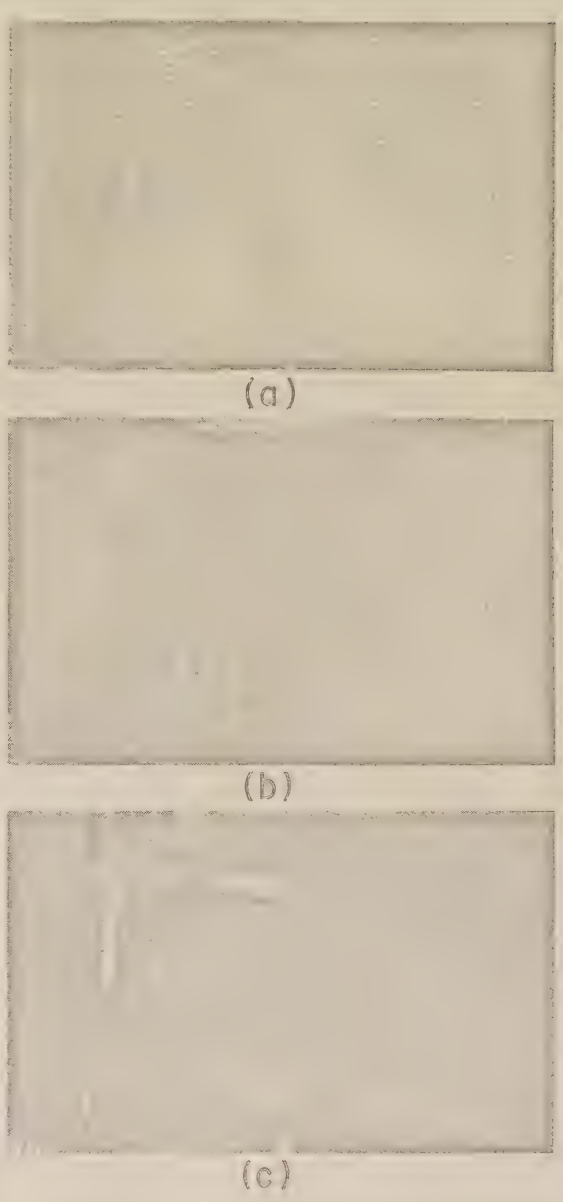

FIG. 8. Retrieved images from the recording shown in Fig. 7(a).

The width of the primary maxima and the irradiances of the secondary maxima depend on N. Equation (10) has maxima at points where the denominator vanishes. The irradiance of each of these maxima is proportional to $(N+1)^2$ and occurs when

$$kv\zeta_0/2=l\pi \quad (l=0,\pm1,\pm2,\ldots),$$

i.e.,

$$v=l\lambda/\zeta_0. \tag{11}$$

Thus the two adjacent primary maxima are separated by λ/ζ_0. Similarly, the minima occur when

$$kv(N+1)\zeta_0/2=m\pi \quad (m=0,\pm1,\pm2,\ldots),$$

i.e.,

$$v=\frac{m\lambda}{(N+1)\zeta_0}. \tag{12}$$

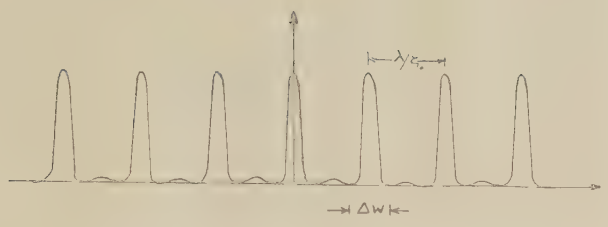

FIG. 9. Multiple-exposure fringes.

Therefore, the separation between the primary maximum of order l and a neighboring minimum is

$$\frac{\Delta w}{2}=\frac{\lambda}{(N+1)\zeta_0}$$

and the angular width of the primary maximum at its base is

$$\Delta w=\frac{2\lambda}{(N+1)\zeta_0} \tag{13}$$

(see Fig. 9).

We have seen that the separation of the primary maxima depends only on the displacement ζ_0, whereas the width of the fringes depends on the multiplicity of the displacements. Thus, the space where the irradiance is minimum between the fringes resulting from (N_0+1) exposures can be occupied by a system of closely packed but nonoverlapping fringes. Let there be n such fringes, each of which is derived from a different light distribution. The extent of the minimum (or zero when N is large) irradiance between the two primary maxima is given by

$$S_0=\frac{\lambda}{\zeta_0}-\frac{2\lambda}{(N_0+1)\zeta_0}$$

$$=\frac{\lambda}{\zeta_0}\left(\frac{N_0-1}{N_0+1}\right). \tag{14}$$

The total width of fringes that can be accommodated in this space is

$$\sum\Delta w=\sum_n\frac{2\lambda}{(N_n+1)\zeta_n}, \tag{15}$$

where ζ_n is the displacement and N_n is the number of exposures of the nth image. Then

$$S_0=\sum\Delta w. \tag{16}$$

For simplicity, we assume that the widths of all the fringes contributing to $\sum\Delta w$ are comparable, so that we can write

$$(N_n+1)\zeta_n\simeq(N_0+1)\zeta_0 \tag{17}$$

and

$$\sum\Delta w\simeq n\frac{2\lambda}{(N_0+1)\zeta_0}. \tag{18}$$

Equations (14), (16), and (18) give

$$n=\frac{N_0-1}{2}. \tag{19}$$

In addition to n, one more signal can be stored in the main system whose two adjacent fringes are separated by S_0. So that the total number of signals that can be multiplexed becomes

$$n+1=\frac{N_0+1}{2}. \tag{20}$$

This relation gives the theoretical limit of the number of images that can be stored, or the channel capacity of the technique, without any cross talk. As an example, for $N_0=15$, according to Eq. (20) we get $(n+1)=8$.

The two primary maxima of the main system of fringes cannot be separated infinitely by decreasing ζ_0. This is limited by the angle of scattering of the diffuser. The available dynamic range of the emulsion also imposes an upper limit on the number of channels that can be recorded.[6] The cross talk due to nonlinear storage has been discussed in Ref. 6. Apart from these, any irregularity of the movement of the photographic plate decreases the channel capacity.

GENERAL

When recording with two exposures, it is always difficult to record more than two images without cross talk. However, with multiple exposures, the resulting more-or-less-flat minimum permits storing a large number of images. Secondary maxima may present some problems, but their irradiances are very low compared to that of principal maxima for large N. Burch and Tokarski[11] have suggested a technique with which it is possible to get rid of the secondary maxima. According to them, if the exposures are in the ratio of binomial coefficients and the plate is given equal displacements between the exposures, the intermediate maxima can be made to disappear.

A binary filter was employed in this method for separating out the images recorded on a single frame. Such a filter has only the values one or zero as its amplitude transmittance and consists of apertures and stops. Because in this case we are dealing with rectilinear fringes, an array of slits and bars has been found more practicable. Such an array, with its slits centered at the maximum transmittances, will let pass the required information. But in the general case of more than one fringe system, depending upon the displacements, there will be resonances due to the superpositions of bright fringes of two or more systems. A slit located at such a resonant fringe would transmit information about all of the images contributing to the resonant fringe. So a regular array of slits is not at all useful. Instead, a single slit can give satisfactory retrieval of the images, as it

can be located at the bright fringe that belongs solely to one particular image. Alterations of the appearance of the image of a coherently illuminated object by a binary filter have been described by Abbe in his theory of image formation in a microscope.

CONCLUSIONS

We have described the feasibility of storing a number of images by use of a technique in which the Fourier transform of the signal is modulated by the factor $[1+\exp(jkv\zeta_0)]$ or

$$\frac{1-\exp[jkv(N+1)\zeta_0]}{1-\exp(jkv\zeta_0)},$$

as the case may be. The only drawback of the method is that the retrieved images are modulated by the diffuser function. A large number of frequencies are stopped by the spatial filter used in the process of retrieval. The width of the slit used as the filter is chosen to suit the width of the maximum fringes, to limit cross talk to a minimum.

A coherent light source has been employed in the recording as well as in the retrieval of the images. As has already been shown elsewhere,[13] such recording can be done with incoherent light, the only restriction being the minimum possible distance between the diffuser and the photographic plate. This makes the technique useful outside the laboratory.

The method has been found ideal for continuous-tone signals. The operations involved are straightforward in concept and relatively simple, compared to the other methods of image multiplexing. The maximum number of channels that can be multiplexed is controlled by the number of exposures for each signal, the amount of relative displacement of the identical signals on the photographic plate between exposures, and the dynamic range of the emulsion. The poor quality of the retrieved images shown in the examples is due to the extremely poor conditions under which the experiments were performed. The deterioration is attributed mainly to the irregularity of the motion of the photographic plate, the limited range of variation provided with the shutter system for adjusting the time of exposure, and stray light due to scattering at the optical surfaces.

The immediate possible applications of the technique are multicolor storage on black-and-white films and reversal of contrast in digital and continuous-tone signals.

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REFERENCES

* On leave from the National Physical Laboratory of India, New Delhi-12.

[1] Historical account of carrier-frequency photography is contained in a paper by K. Biedermann, Opt. Acta **17**, 631 (1970).

[2] E. N. Leith and J. Upatnieks, J. Opt. Soc. Am. **54**, 1295 (1964).

[3] R. J. Collier and K. S. Pennington, Appl. Opt. **6**, 1091 (1967).

[4] H. J. Caulfield, Appl. Opt. **9**, 1218 (1970).

[5] J. D. Armitage and A. W. Lohmann, Appl. Opt. **4**, 399 (1965).

[6] P. F. Mueller, Appl. Opt. **8**, 267 (1969).

[7] E. N. Leith, A. Kozma, J. Upatnieks, J. Marks, and N. Massey, Appl. Opt. **5**, 1303 (1966).

[8] A. A. Friesem and J. L. Walker, Appl. Opt. **9**, 201 (1970).

[9] S. C. Som and R. A. Lessard, J. Opt. Soc. Am. **61**, 1240 (1971).

[10] S. Debrus, M. Françon and M. May, in *Optical Instruments and Techniques*, edited by J. Home Dickson (Oriel Press, Newcastle upon Tyne, 1969), p. 319.

[11] J. M. Burch and J. M. J. Tokarski, Opt. Acta. **15**, 101 (1968).

[12] J. M. Burch, A. E. Ennos, and R. J. Wilton, Nature **209**, 1015 (1966).

[13] S. Debrus, M. Françon, and C. P. Grover, Opt. Commun. **4**, 172 (1971).